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The dynamics of S0 galaxies and their Tully–Fisher relation

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ABSTRACT

This paper investigates the detailed dynamical properties of a relatively homogeneous sample of disc-dominated S0 galaxies, with a view to understanding their formation, evolution and structure. By using high signal-to-noise ratio long-slit spectra of edge-on systems, we have been able to reconstruct the complete line-of-sight velocity distributions of stars along the major axes of the galaxies. From these data, we have derived both model distribution functions (the phase density of their stars) and the approximate form of their gravitational potentials.

The derived distribution functions are all consistent with these galaxies being simple disc systems, with no evidence for a complex formation history. Essentially no correlation is found between the characteristic mass scalelengths and the photometric scalelengths in these galaxies, suggesting that they are dark-matter dominated even in their inner parts. Similarly, no correlation is found between the mass scalelengths and asymptotic rotation speed, implying a wide range of dark matter halo properties.

By comparing their asymptotic rotation speeds with their absolute magnitudes, we find that these S0 galaxies are systematically offset from the Tully–Fisher relation for later-type galaxies. The offset in luminosity is what one would expect if star formation had been suddenly switched off a few Gyr ago, consistent with a simple picture in which these S0s were created from ordinary later-type spirals which were stripped of their star-forming interstellar medium when they encountered a dense cluster environment.

Key words: galaxies: elliptical and lenticular, cD – galaxies: kinematics and dynamics – galaxies: structure.

1 INTRODUCTION

Because S0 galaxies seem to have properties intermediate between elliptical and spiral galaxies, Hubble (1936) placed these gas-poor disc systems between the spirals and ellipticals, at the bifurcation of his tuning fork galaxy classification scheme. However, three-quarters of a century later, it remains an open question as to whether this arrangement in any way reflects the physical origins of S0 galaxies.

One approach to addressing question of this kind has been to search directly for signs of evolution in galaxy morphologies by observing samples of these systems over a wide range of redshifts. In a classic study of this kind, Butcher & Oemler (1978) found that the fraction of blue galaxies in clusters was much higher in the past than it is now. They surmised that blue spirals were being converted to earlier-type systems. This discovery fitted in extremely well with Gunn & Gott’s (1972) suggestion that S0 galaxies could form from spiral galaxies in the dense environment of a cluster via tidal and

ram pressure stripping. More recently, high-resolution observations (e.g. Lavery, Pierce & McClure 1992; Couch et al. 1994) have confirmed that the blue galaxies in high-redshift clusters are, indeed, relatively normal spiral galaxies, which could well be the progenitors of S0 systems.

The only problem with such analyses is that one is necessarily observing different galaxies in the nearby and distant samples, so any inference about the evolution from one type to another is of a circumstantial nature. A convincing case therefore requires that one looks in some detail at the ‘finished articles,’ in order to find any archaeological evidence for the proposed evolution. As galaxies are intrinsically dynamical entities, one should be able to extract important clues from their stellar kinematics, as derived from absorption-line spectra, as well as their photometric properties. With high-quality spectral data, one can measure the full line-of-sight velocity distribution (e.g. Fisher 1997; Koprolin & Zeilinger 2000), providing information not only on the motions of the stars, but also the gravitational potential responsible for the motions.

For S0 galaxies, one important piece of stellar-dynamical

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evidence would be provided by an analysis of the Tully–Fisher relation. In later-type disc galaxies, there is a strong correlation between circular rotation speed and optical luminosity (Tully & Fisher 1977), and this relationship becomes even tighter when one looks in the near infrared (Pierce & Tully 1992). If S0 galaxies formed in a relatively benign way from spiral galaxies, one would expect that their optical luminosities and circular rotation speeds would be little affected by the process, so a Tully–Fisher relation should still be apparent; the only significant difference would be that the stripping of their gas would switch off the star formation process, so the optical luminosities of the S0s should fade over time, shifting the zero-point of the relation.

To date, the most thorough search for a Tully–Fisher relation in S0 galaxies was that made by Neistein et al. (1999). This analysis is complicated by the fact that there is no simple measure of the circular speed in an S0 galaxy: there is no gas at large radii moving in circular orbits, and the stars follow significantly elliptical orbits, so their mean streaming velocity at any radius is lower than the local circular velocity. Neistein et al. overcame the problem by appealing to the equations of galactic dynamics: by making a few simplifying assumptions, they were able to use the asymmetric drift equation (Binney & Tremaine 1987) to combine the mean streaming velocity and velocity dispersion of the stars in order to estimate the circular velocity at each radius.

Although this analysis revealed some evidence for a trend between *I*-band luminosity and circular speed, Neistein et al. found a huge scatter in the relation, and that there was very little offset in the mean from the Tully–Fisher relation of later-type galaxies. They therefore concluded that these systems could not all have formed from the simple stripping of spiral galaxies. Instead, they suggested that the S0 classification actually represents a rather heterogeneous class of galaxies, which formed through a rather wide variety of processes. They further suggested that the absence of an offset in the Tully–Fisher relation could be understood if the S0 galaxies have more massive discs, so any fading in their luminosities is offset by the larger number of stars.

In order to explore these conclusions a little further, this paper presents a detailed dynamical analysis of six S0 galaxies. These galaxies have been selected to contain relatively small central bulges. If any S0s formed from simple stripping processes, one would expect their bulges to be little affected. Thus, by selecting S0s with the small bulges characteristic of later-type spirals, one might hope to pick out a relatively homogeneous subsample of systems that formed via this route. Unfortunately, it is only when S0 galaxies are very close to edge-on that one can reliably determine that their bulges are small. As Neistein et al. (1999) demonstrated, the line-of-sight integration of starlight through such an edge-on disc means that there is quite a large correction to convert the observable mean line-of-sight velocity into the circular streaming velocity of the stars. As a further complication, the observed velocity distribution for any line of sight through an edge-on disc will be highly non-Gaussian, as a result of the contribution from stars at large radii with small line-of-sight velocities. A dynamical analysis based on moments derived from a Gaussian fit to the line-of-sight velocity distribution is therefore prone to systematic error. To obviate these difficulties, the current analysis uses data with a high enough signal-to-noise ratio for the complete line-of-sight velocity distribution to be derived, and these data are then fitted to a complete dynamical model in order to derive both the stellar distribution function and the gravitational potential needed for the Tully–Fisher relation.

The remainder of the paper is laid out as follows. Section 2

describes the sample, the data analysis, the model fitting, and the resulting distribution functions and rotation curves. Section 3 discusses the correlations in derived quantities, with particular reference to the Tully–Fisher relation. Section 4 presents the conclusions that can be drawn from this analysis.

2 DATA ANALYSIS

2.1 The sample

The galaxies chosen for this study were selected from the sample presented in Kuijken, Fisher & Merrifield (1996). This galaxy sample contains 28 early-type disc galaxies, and was originally observed to search for counter-rotating populations, so high signal-to-noise ratio spectra were obtained. Details of the spectroscopic observations and standard data reduction can be found in Kuijken et al. (1996). From this sample we selected the six S0 galaxies of with similar mean rotation speeds, so that there is some chance that the systems are comparable in their dynamics. We also selected galaxies that are close enough to edge-on for it to be apparent that the systems are disc-dominated, with relatively small bulges (and thus that a simple evolutionary path from later-type spiral galaxies is plausible). Images of the sample galaxies are shown in Fig. 1.

2.2 Kinematic analysis

Line-of-sight velocity distributions (LOSVDs) were extracted from the reduced spectra using the unresolved gaussian decomposition (UGD) algorithm (Kuijken & Merrifield 1993). This method models each LOSVD as the sum of a set of unresolved Gaussians with fixed means and dispersions. The amplitudes of the Gaussians are varied so as to minimize the difference between the galaxy spectrum and the model derived by convolving the LOSVD with a suitable template star spectrum. This approach has the advantage that it does not force any particular functional form on the LOSVD, beyond the smoothness imposed by the widths of the component Gaussians. It is therefore well-suited to modelling complex systems like edge-on disc galaxies, where integration along the line of sight, potentially through multiple components, can make the shape of the LOSVD rather complex.

In order to increase the signal-to-noise ratio of the resulting kinematic data, the two-dimensional LOSVD as a function of position along the major axis, $F(v_{\text{los}}, R)$, was assumed to have the

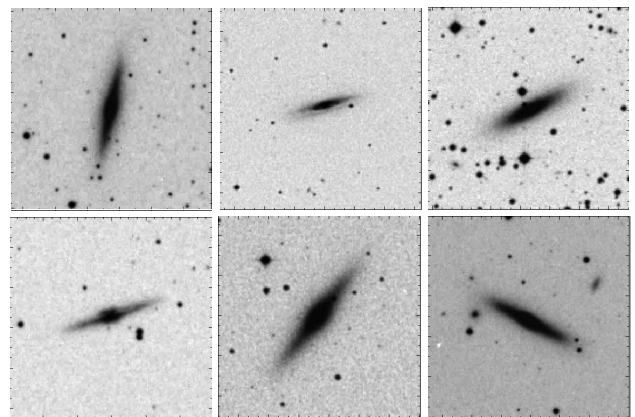


Figure 1. Images from Digitized Sky Survey for the sample of S0 galaxies. From left-to-right and top-to-bottom: NGC 1184, 1611, 2612, 3896, 4179 and 5308.

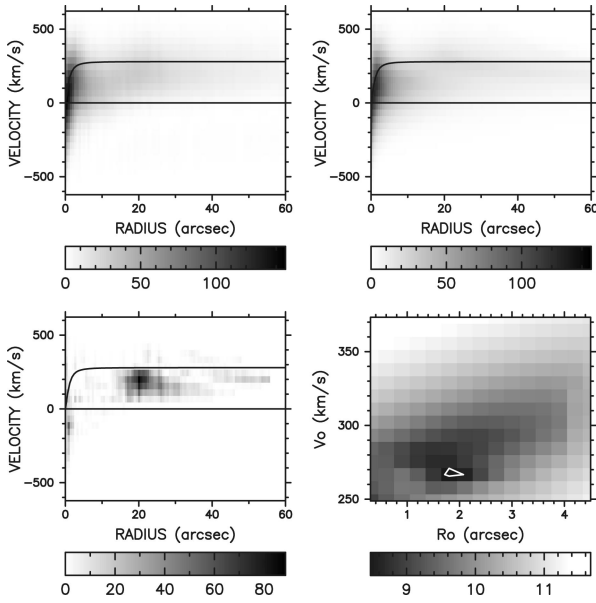


Figure 2. Top left: The line-of-sight velocity distribution as a function of projected radius along the major axis of NGC 1184. Top right: the corresponding quantities for the best-fitting dynamical model. Bottom left: plot of $[(\text{data-model})/\sigma]^2$, showing where the major χ^2 residuals arise. Bottom right: $\ln(\chi^2)$ as a function of the adopted parameters for the gravitational potential, (r_0, v_0) ; the solid contour shows where $\ln(\chi^2) = \ln(1.1\chi^2_{\min})$.

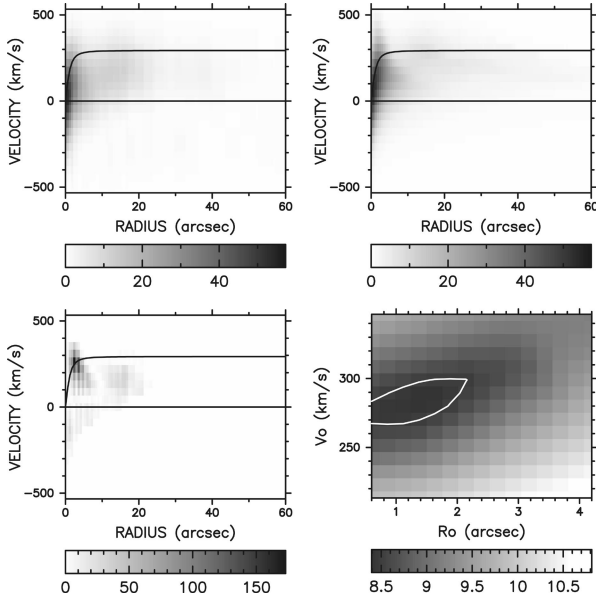


Figure 3. Same as in Fig. 2 for NGC 1611.

symmetry of an edge-on axisymmetric disc system, so that $F(v_{\text{los}}, R) \equiv F(-v_{\text{los}}, -R)$. We therefore determined the kinematic coordinates of the centre of each galaxy by finding the point in $F(v_{\text{los}}, R)$ at which this symmetry is most closely obeyed. We then averaged the data from the two sides of each galaxy. The resulting mean estimates for $F(v_{\text{los}}, R)$ are shown in the top-left panels of Figs 2, 3, 4, 5, 6 and 7.

2.3 Dynamical analysis

Having derived these kinematic data, we must now attempt to

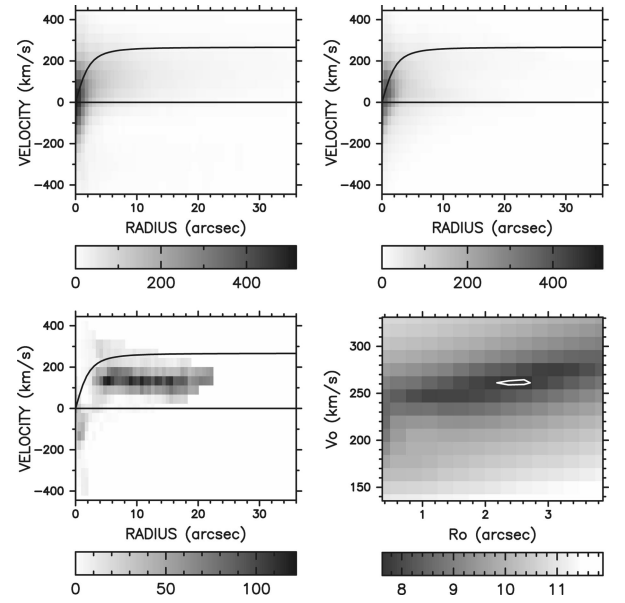


Figure 4. Same as in Fig. 2 for NGC 2612.

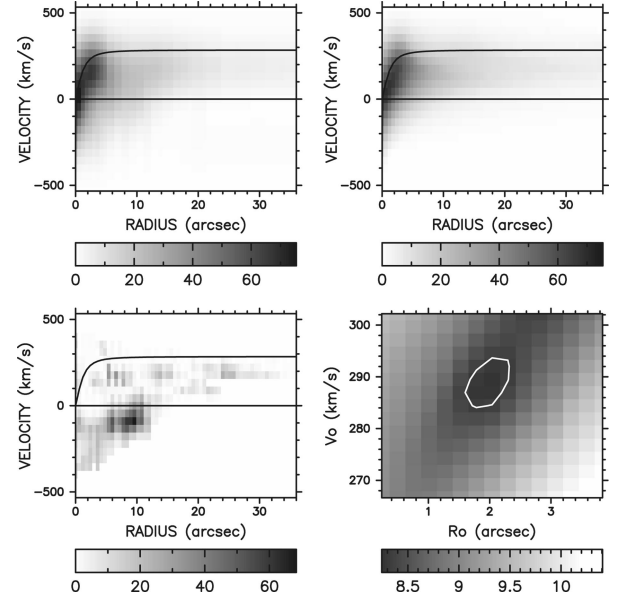


Figure 5. Same as in Fig. 2 for NGC 3986.

describe them using a dynamical model. The simplest credible model for the major axis kinematics of a galaxy involved fitting them to a two-integral distribution function, $f(E, L)$, which describes the phase-space density of stars, where E is the energy and L is the angular momentum of the stars about the symmetry axis, two of the integrals of motion (Binney & Tremaine 1987). Such a model would be exact for an infinitely thin axisymmetric disc, but it is also a credible approximation for a system of finite thickness. Defining the usual polar coordinates, the energy in the z -direction, $E_z = \Phi(R, z) - \Phi(R, 0) + (1/2)v_z^2$, is approximately an integral of motion for a thin disc. A system whose distribution function takes the form $f(E, L)g(E_z)$ will have dynamics in the $z = 0$ plane identical to those of an infinitely thin disc with a distribution function $f(E, L)$. Thus, the dynamics in the plane of the disc can credibly be modelled by treating the major-axis kinematics as if they were those of an infinitely thin disc.

Mathieu & Merrifield (2000) presented an algorithm by which the observed density of stars as a function of projected radius and line-of-sight velocity, $F(R, v_{\text{los}})$ could be iteratively inverted to find the distribution function, $f(E, L)$, that would produce such observable kinematics. This method builds an estimate of the distribution function using just the data from the upper part of the line-of-sight velocity distribution where the velocities exceed the circular velocity. If the correct gravitational potential is adopted, then the rest of the velocity distribution automatically matches the data; however, a mismatch will occur if the wrong potential is assumed. Thus, this algorithm returns not only an estimate for the disc distribution function, but also constrains the form of the gravitational potential.

In principle, the gravitational potential in the disc plane could take any form, but the data are not of high enough quality to allow a

completely non-parametric derivation. We therefore adopt the simple but sufficiently general form of a softened isothermal sphere potential of the form

$$\Phi(r) = \frac{v_0^2}{2} \ln \left(1 + \frac{r^2}{r_0^2} \right). \quad (1)$$

For this potential, the circular velocity can be written

$$v_c(r) = \frac{v_0 r}{\sqrt{r^2 + r_0^2}}, \quad (2)$$

with the parameters r_0 and v_0 specifying how quickly the rotation curve rises and its asymptotic value.

Using the iterative algorithm, distribution functions have been derived for all the sample galaxies. Fig. 8 shows the best-fitting distribution functions obtained in this way. All the systems show the single concentration of low angular-momentum material, characteristic of a disc. Thus, there is no evidence even in these detailed dynamical models of any peculiarities in the stellar dynamics that one might expect if these systems had formed in a spectacular manner such as in a merger (Bekki 1998).

To assess the reliability of the fitting process, Figs 2, 3, 4, 5, 6 and 7 show the ‘observable’ kinematics of these dynamical model, $F(R, v_{\text{los}})$, and the difference between these predictions and the observed kinematics (normalized by the uncertainty in the observations). Finally, these figures also show how rapidly the goodness of fit (in a χ^2 sense) degrades as one goes away from the optimal values for r_0 and v_0 in the gravitational potential. The best-fitting values for r_0 and v_0 are listed in Table 1.

So far in our analysis we have assumed that the galaxies are perfectly axisymmetric and we used average data from both sides of the galaxy. However, the kinematics of these galaxies show small asymmetries and we also performed the fitting process on each side of the galaxies separately. We use the best-fitting values of r_0 and v_0 on each side of the galaxy to estimate the dispersion of r_0 and v_0 around the mean for each galaxy. An example of fits on both sides of one galaxy (NGC 3986) is shown in Figs 9 and 10.

Clearly, in these galaxies there are some systematic residuals in the difference between model and data. Indeed, the minimum values of χ^2 are well above what one might expect for a formally good fit. However, given the assumptions involved as to the separable form of the distribution function and the adopted parametric function for the gravitational potential, these small residuals are not particularly surprising. In order to assess their impact on our subsequent analysis, we have explored more sophisticated models for the distribution function. In particular, we have investigated what happens if our assumption of a single-component disc-like distribution function is relaxed, by explicitly adding the contribution from a central bulge component (rather than treating it as part of the disc). To this end, we adopt a simple bulge model with a distribution function of the form

$$f(E, L) = \alpha [\exp(-\beta E) - \exp(-\beta E_0)] \exp(\gamma L), \quad (3)$$

where $(E \leq E_0)$ is the energy of a star and L its total angular momentum, and where α , β and γ are constants (see Jarvis & Freeman 1985). We then computed the line-of-sight velocity distribution corresponding to this distribution function and subtract it from the observed line-of-sight velocity distribution. The choice of the constants remains somewhat arbitrary as a full bulge-disc decomposition is underconstrained, but we stick to values of the parameters such that the estimate of line-of-sight velocity distribution of the disc alone (after subtracting the line-of-sight

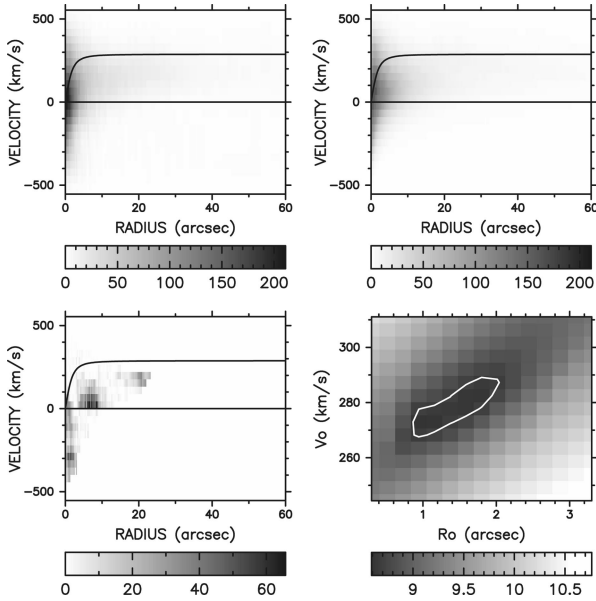


Figure 6. Same as in Fig. 2 for NGC 4179.

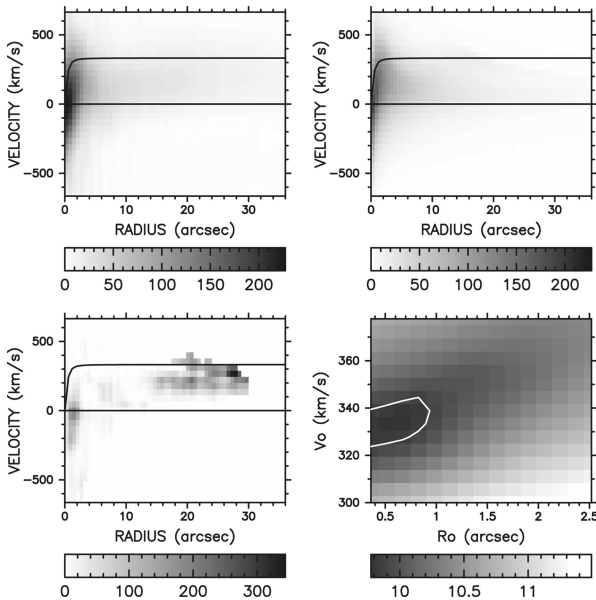


Figure 7. Same as in Fig. 2 for NGC 5308.

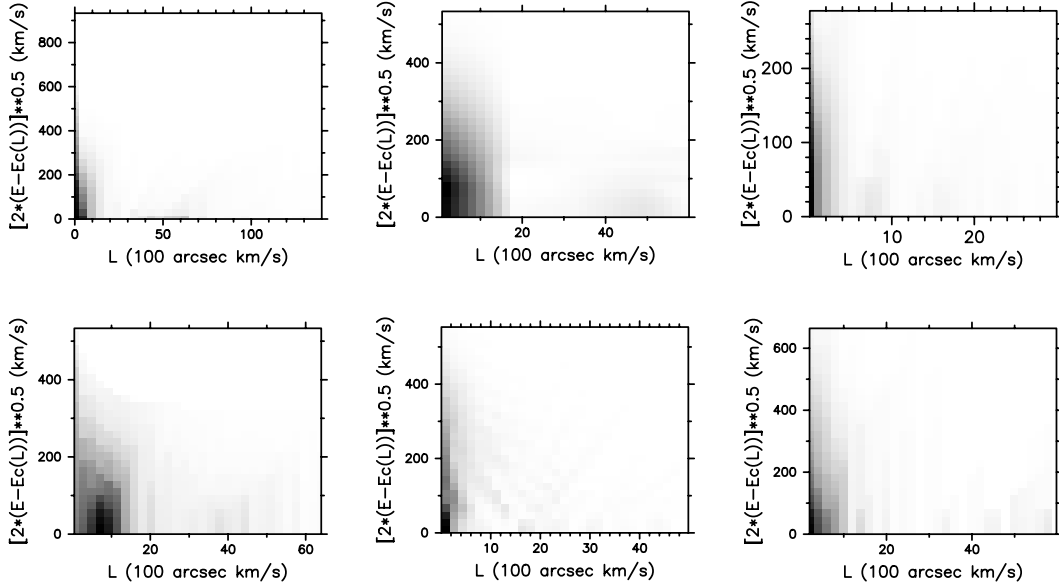


Figure 8. The disc distribution functions for the galaxies as derived iteratively from their line-of-sight kinematics using the best-fitting gravitational potentials.

Table 1. Estimates of the parameters (r_0, v_0) for the gravitational potential, estimate of the photometric disc scale length r_d and absolute I and H magnitudes for each galaxy.

Name	v_0 [km s $^{-1}$]	r_0 [arcsec]	r_d [arcsec]	M_I	M_H
NGC 1184	271 ± 17	1.4 ± 0.4	21.3 ± 1.5	-21.1	-23.0
NGC 1611	271 ± 15	1.8 ± 0.3	12.1 ± 0.3	-21.5	-23.4
NGC 2612	252 ± 11	2.2 ± 0.3	12.8 ± 0.2	-19.9	-21.8
NGC 3986	289 ± 06	2.4 ± 0.6	07.6 ± 1.1	-21.6	-23.5
NGC 4179	275 ± 07	1.7 ± 0.4	12.8 ± 0.5	-20.9	-22.8
NGC 5308	321 ± 17	0.5 ± 0.1	16.5 ± 0.4	-21.6	-23.5

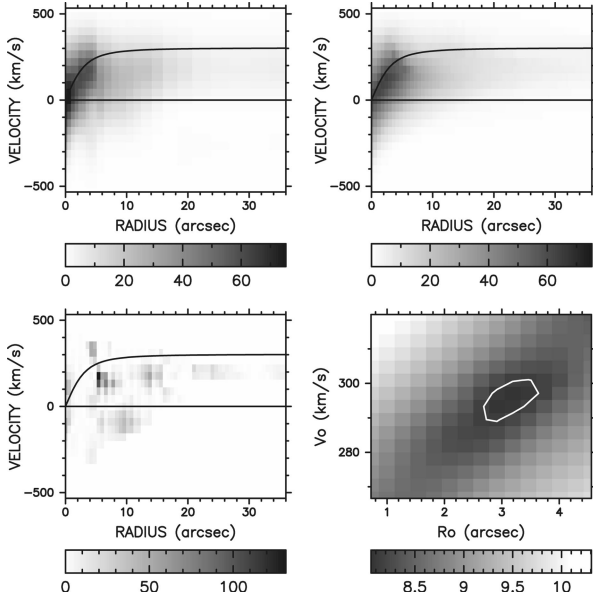


Figure 9. Same as in Fig. 2 for NGC 3986, using data on the ‘left’ side of the galaxy.

velocity distribution produced by the bulge from the observed line-of-sight velocity distribution) is positive almost everywhere. Rather surprisingly, this extra spherical component makes very little difference to the best-fitting gravitational potential: Fig. 11

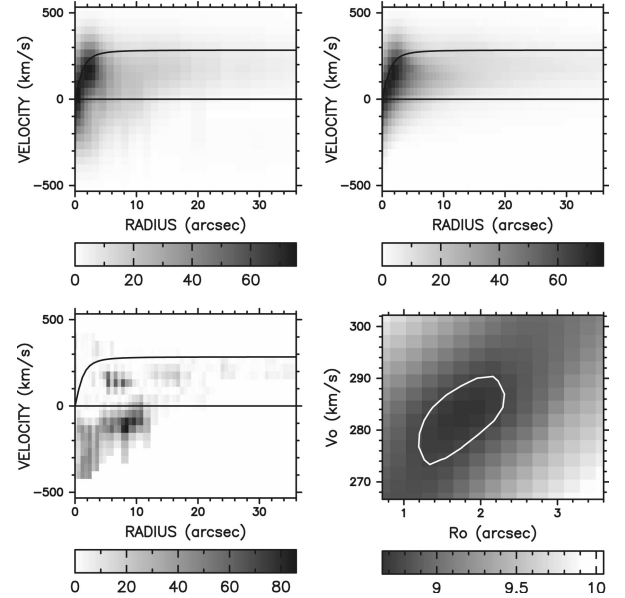


Figure 10. Same as in Fig. 2 for NGC 3986, using data on the ‘right’ side of the galaxy.

illustrates the best-fitting model for NGC 1184, in which the constraints on r_0 and v_0 are close to those in the pure disc model. It would thus appear that the simple model adopted above does a robust job of estimating the gravitational potential even where the assumption of a thin disc is not strictly valid.

2.4 Photometric analysis

B-band integrated magnitudes for the sample galaxies have been taken from the RC3 catalogue, where available, or from the Lyon–Meudon extragalactic data base (LEDA) otherwise. These have been converted to absolute magnitudes using distance estimates from the LEDA data base, where available. For NGC 1611 and 2612, as no distance is available, we estimate the distance using the systemic velocity derived from our spectra assuming

$H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$. It would be useful to study the integrated photometric properties of these systems in a number of bands. Unfortunately, such data are unavailable for most systems. However, the spread in the integrated colors of S0 galaxies is very small: for the S0 galaxies in the sample of Persson, Frogel & Aaronson (1979), $B - H$ has a mean value of 3.9 and a scatter of only ~ 0.3 , while $B - I$ has a mean value of 2 and a scatter of ~ 0.3 for the S0 galaxies in the sample of Neistein et al. (1999). As we shall see below, these scatters are comparable to other sources of uncertainty, so for this analysis we can simply apply the mean colour corrections in order to estimate absolute magnitudes in the I and H bands. The resulting magnitudes are listed in Table 1.

The principal spatially resolved photometric quantity of interest in these disc-dominated systems is the disc scale-length. To determine this quantity, we first estimate the intensity profiles, $I(r)$, as a function of radius by integrating the line-of-sight velocity

distributions derived above with respect to velocity. We adopt this approach in preference to using imaging data, as it guarantees that the photometric and kinematic measurements are probing the same stellar population. We then approximate the starlight of the disc at large radius by fitting a function of the form

$$I_{\text{mod}}(r) = 2A_d |r| K_1(|r|/r_d), \quad (4)$$

where A_d and r_d are free parameters, and K_1 is a modified Bessel function, which represents the projected density profile of an edge-on exponential disc. With only rather noisy photometric profiles and no detailed surface photometry for our galaxies, we only fit a disc model at large radius as fitting a bulge-disc model proves very much underconstrained and does not give reliable values for the parameters of the disc and bulge. The best-fitting photometric models are shown in Fig. 12 where the models are fitted independently on each side of the galaxy, and the derived photometric scalelengths r_d are given in Table 1. This quantity differs from the photometric scalelength usually estimated by fitting two-component bulge-disc models.

3 DISCUSSION

Having derived the dynamical and photometric properties of these galaxies, we are now in a position to look for clues to their origins. Fig. 13 shows the physical parameters of the rotation curves in these galaxies. There are no signs of any correlation between r_0 and v_0 , suggesting that these galaxies occupy dark haloes with the usual wide range of characteristics, although the sample is really too small to say anything definitive. Similarly, there is no discernable correlation between the mass scale-length, r_0 , and the photometric scale-length, r_d , (see Fig. 14) arguing against Neistein et al.'s (1999) suggestion that these galaxies should be more dominated by the mass in their stellar discs than normal spiral galaxies.

A more interesting result comes when we look at the Tully–Fisher relation for S0 galaxies. Fig. 15 shows the I -band relation derived by Neistein et al. (1999), which lie quite close to the Tully–Fisher relation for normal spiral galaxies (Pierce & Tully 1992), but with a large rms scatter of ~ 0.6 mag about the best-fitting line parallel to the standard Tully–Fisher relation. The

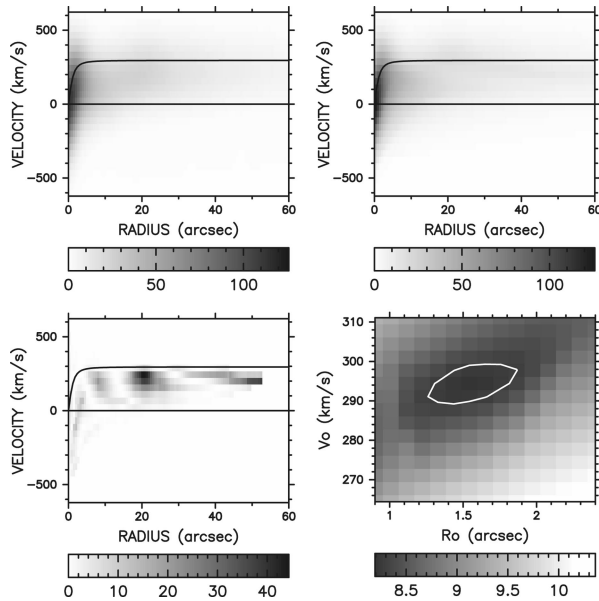


Figure 11. Same as in Fig. 2 for a bulge-disc model of a NGC 1184.

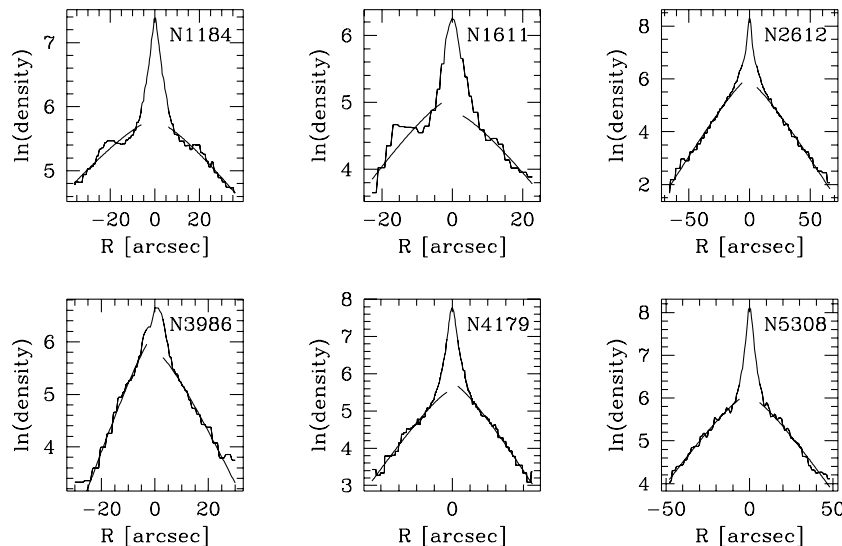


Figure 12. Plot of the logarithm of the projected luminosity density as a function of projected radius along the major axes of the six sample galaxies, as derived from their line-of-sight velocity distributions. The overplotted smooth lines show the best-fitting disc model.

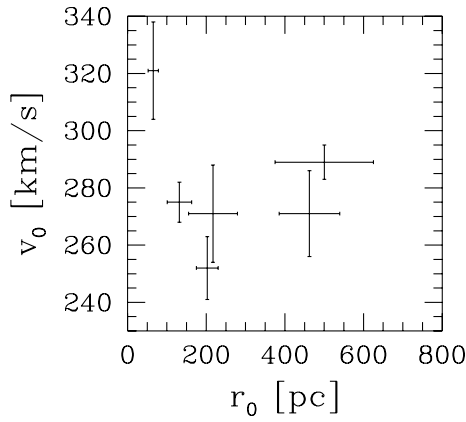


Figure 13. Plot of the estimates of the maximum circular velocity v_0 versus the estimates of the parameter r_0 .

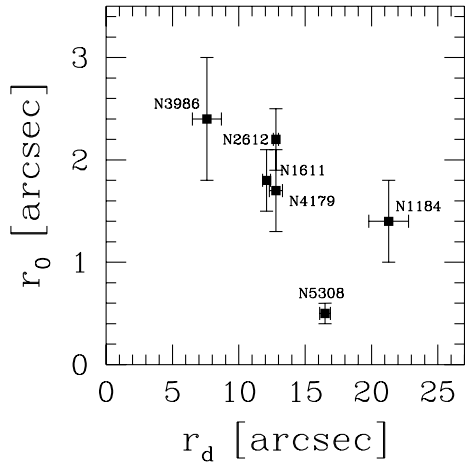


Figure 14. Plot of the estimates of photometric disc scale length r_d versus the estimates of the parameter r_0 for the gravitational potential.

galaxies in the current sample lie systematically below the Neistein et al. galaxies. With the galaxies all selected to have comparable rotation speeds, we clearly cannot derive a slope for the Tully–Fisher relation from these data, but fixing the slope to that of the relation for normal spiral galaxies, we find that the best-fitting line is offset from the spiral galaxy relation by ~ 1.8 mag, with a scatter about the best-fitting line of only ~ 0.3 mag. For this fit we exclude NGC 2612 as its distance estimate is rather uncertain because of a small systemic velocity. Even allowing for the small sample size, this scatter is smaller than that in the Neistein et al. sample at a statistically significant level.

This small scatter and offset in the Tully–Fisher relation by ~ 1.8 mag in the I -band is what one would expect if star formation had been suddenly switched off a few Gyr ago, so that these S0 galaxies contained just the old stellar population of a normal spiral galaxy. Using stellar population models (Charlot & Bruzual 1991), assuming S0s galaxies had had similar formation histories as late-type spirals until a few Gyr ago, we would expect the stellar population of S0s to have faded significantly, resulting in a noticeable offset in I -magnitude, such as the one observed in our sample.

This point is made even more dramatically if we convert to estimated H -band magnitudes using the prescription in Section 2. In this band, the luminosity is dominated by the old stellar populations; as Fig. 16 shows, the S0s in the current sample lie

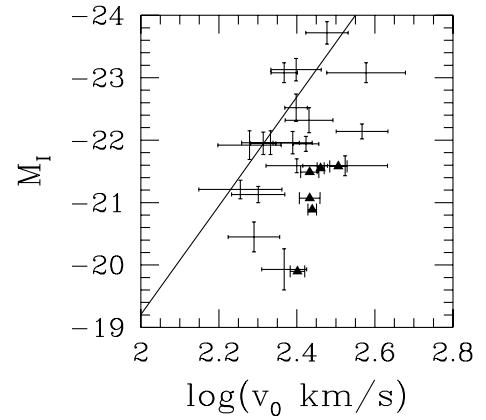


Figure 15. Absolute I -band magnitude versus $\log(v_0 \text{ km s}^{-1})$ for the sample of S0 galaxies in Neistein et al. (1999), and those in this analysis (filled triangles). The line shows the I -band Tully–Fisher relation for later-type spirals from Pierce & Tully (1992).

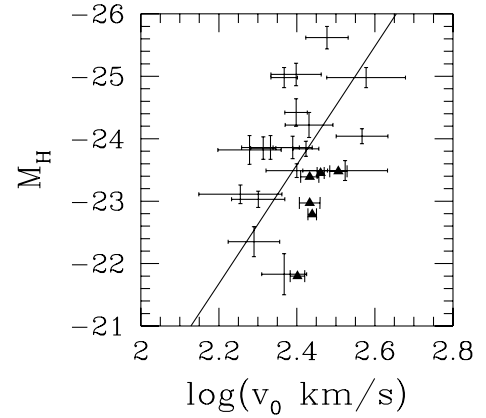


Figure 16. Estimated absolute H -band magnitude versus $\log(v_0 \text{ km s}^{-1})$ for the sample of S0 galaxies in Neistein et al. (1999), and those in this analysis (filled triangles). The line shows the H -band Tully–Fisher relation for later-type spirals from Pierce & Tully (1992).

quite close to the Tully–Fisher relation for later-type spiral galaxies, suggesting that their old stellar populations are rather similar.

4 CONCLUSIONS

In this paper, we have calculated the first detailed dynamical models for a small sample of edge-on S0 galaxies with small bulges. In addition to producing distribution functions for these disc-dominated systems, which look very much as one would expect for normal disc systems, the analysis also returned estimates for the parameters of their gravitational potentials.

The interpretation of these data all points to a simple picture in which these systems were formed by the stripping of gas from normal spiral galaxies. The distribution functions are all well modelled by unexceptional stellar discs, similar to those expected in the old stellar populations of spiral galaxies. In addition, the galaxies obey a reasonably tight Tully–Fisher relation, which is offset from the relation for normal spiral galaxies by the amount that one would expect if star formation had been shut off a few Gyr ago, so that all that remains in these systems are the rather fainter old stellar populations.

This result appears to conflict with Neistein et al.'s (1999) analysis, which showed a much greater scatter in the Tully–Fisher relation with less systematic offset. Part of the difference may be a result of the lower signal-to-noise ratio of the data in their larger sample, which limited their ability to carry out detailed dynamical modelling, particularly for galaxies that lie very close to edge-on. However, there is also a systematic difference in the way that the samples were selected: the edge-on galaxies in the analysis of this paper were specifically chosen to contain small bulges. This selection criterion means that these galaxies are prime candidates to have formed from gas-stripped spiral galaxies. If, as Neistein et al. suggest, S0s are a ‘mixed bag’ that formed in a variety of ways, it should come as no surprise that this particular subsample obey a tight Tully–Fisher relation that is not seen in the general population of S0s. To test such hypotheses, we ultimately need data of the quality presented in this paper for a much larger sample of galaxies, extending both the range of absolute magnitudes and of other parameters such as the bulge size.

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